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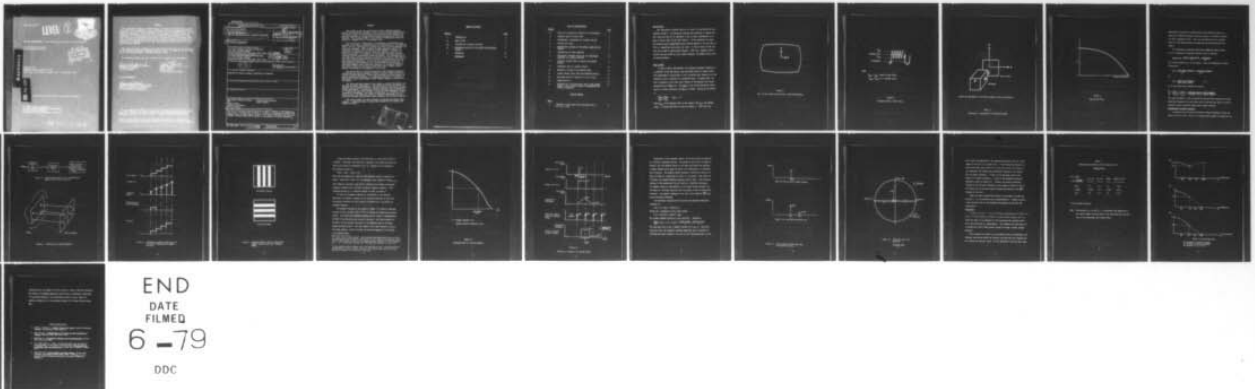DISPLAY MEASUREMENTS. CAN MTF ANALYSIS BE USED ON MATRIX DISPLA--ETC(U)
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DISPLAY MEASUREMENTS --- Can MTF Analysis Be Used on Matrix Displays?

System Technology Branch
System Avionics Division

February 1979
TECHNICAL REPORT AFAL-TR-79-1030
Final Report for Period 1 January 1977 - 30 September 1978

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFAL-TR-79-1030	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DISPLAY MEASUREMENTS: Can MTF Analysis Be Used On Matrix Displays		5. TYPE OF REPORT & PERIOD COVERED Final Technical rept. 1 Jan 77 — 30 Sep 78
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard A. Spearnock		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Avionics Laboratory (AFAL/AAT) Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 20030628
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Avionics Laboratory (AFAL/AAT) Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE February 1979
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 17 p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Modulation Transfer Function	Liquid Crystal Displays
MTF	Liquid Crystal
Visual System	
Observor Performance	
Matrix Displays	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The use of modulation transfer function on matrix displays is investigated in this report. An analytical estimate of the MTF of a hypothetical 1000 X 1000 element liquid crystal display is given. The report concludes that modulation transfer function (MTF) can be useful in the analysis of matrix displays.

FOREWORD

This report is one of a collection of three technical reports written under Work Unit 20030628, "Liquid Crystal Display Measurements." The topics covered in these reports were chosen to either support this work unit directly or to help provide needed information for Work Unit 20030626, "The Integrated HUD." This work was accomplished during the period of 1 January 1977 to 30 September 1978.

The first report, "Measurement of Reflectance on Reflective-Type Displays," deals with the specification of reflectance in a two component sense. That is, reflectance is specified by both a diffuse component and a specular component. This formulation seems especially useful for specifying the reflectance of liquid crystal displays. However, the method is not limited to displays alone, but applies to any type of reflecting surface. For example, the reflectance of various aircraft coatings could be investigated using this method. The determination of the reflectance of these coatings is important and work has been done in this area, using methods other than the one of this report, by the Air Force Materials Laboratory. It is felt that specifying reflectance by this method may have advantages over other methods in current use. A simplified example using reflectance functions to calculate luminance and contrast ratio of an optical system which uses a liquid crystal display is included in the Appendix of the report.

The second report, "Can MTF Analysis Be Used On Matrix Displays?," investigates the use of modulation transfer function (MTF) in the evaluation of matrix displays. This report concludes that MTF analysis of matrix displays can be useful. An analytical estimate of the MTF of a hypothetical 1000 X 1000 element liquid crystal display is included in the report.

The third and final report of the series is titled "The Effects of HUD Glow On Visual Performance." This report deals with the effects of residual glow in head-up displays, and the effects of this glow on human visual performance. By using the contrast threshold work of Blackwell, it is shown that even small amounts of glow can have detrimental effects on operator performance. The amount of detriment is a function of the level of glow, the operator's state of luminance adaptation, and the perceived contrast ratio between target luminance and surround luminance.

The author thanks all those involved in helping him prepare these reports. I especially want to thank John Coonrod for his support and review of drafts.

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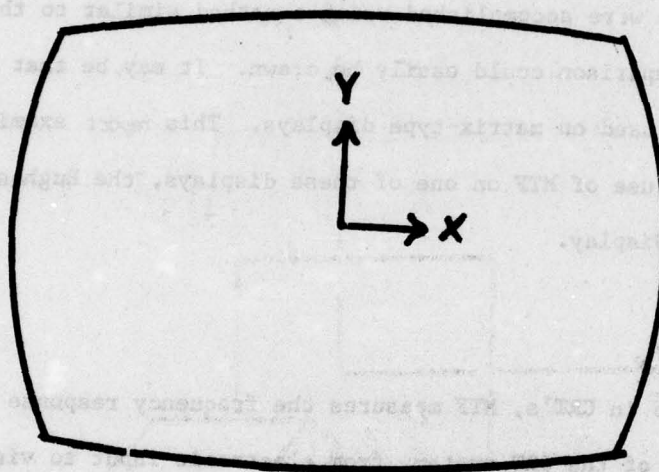# LIST OF ILLUSTRATIONS

LIST OF TABLES

Introduction

MTF (modulation transfer function) is useful in specifying the performance of CRT's. As new matrix displays are developed to replace the CRT, they will have to be evaluated to see if their performance is as good or better than the CRT they replace. If the evaluation of these new displays were accomplished using a method similar to the one used on CRT's, a comparison could easily be drawn. It may be that the MTF concept can be used on matrix-type displays. This report examines theoretically the use of MTF on one of these displays, the Hughes Liquid Crystal Matrix Display.

What is MTF?

As used in CRT's, MTF measures the frequency response (response to a sinewave) of the CRT system, from electronic input to visual output. This measurement is restricted to the X direction only (Figure 1) as the response in the Y direction is considered fixed. To measure MTF, one adds a sinewave to the video input (Figure 2) and measures the output photometrically (Figure 3). The ratio of the output modulation (photometric) to input modulation (voltage) is formed. Modulation is defined as
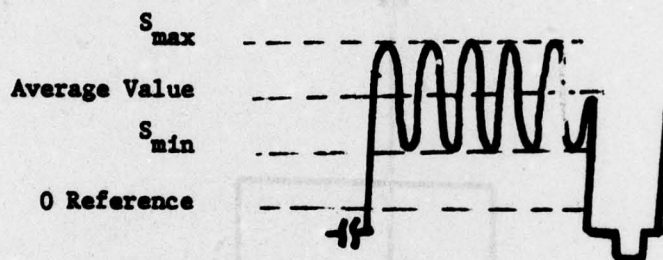
$$\frac{S_{max} - S_{min}}{S_{max} + S_{min}} \qquad S_{min} \geq 0,$$

where S_{max} is the maximum value of the sinusoid and S_{min} the minimum value. A typical MTF curve is shown in Figure 4. This curve was

1

Figure 1.

Face of CRT Indicating Direction of MTF Measurements.

S_{max} — — —
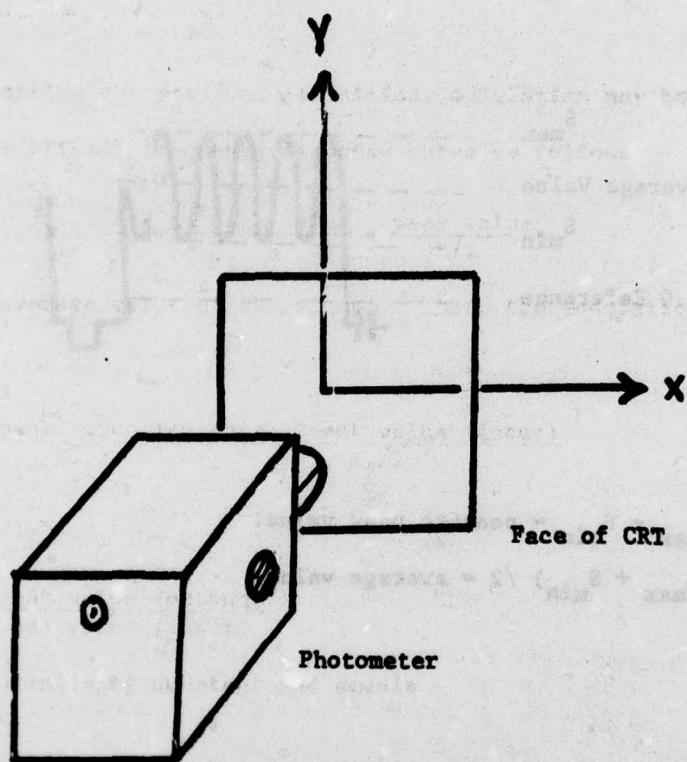
Average Value — — —

S_{min} — — —

0 Reference — — —

NOTE:

$S_{max} - S_{min}$ = peak to peak value.

$(S_{max} + S_{min})/2$ = average value.

Figure 2.

Sinewave Added to Video Input.

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Either the photometer or the CRT is moved in the $\pm$ x direction.
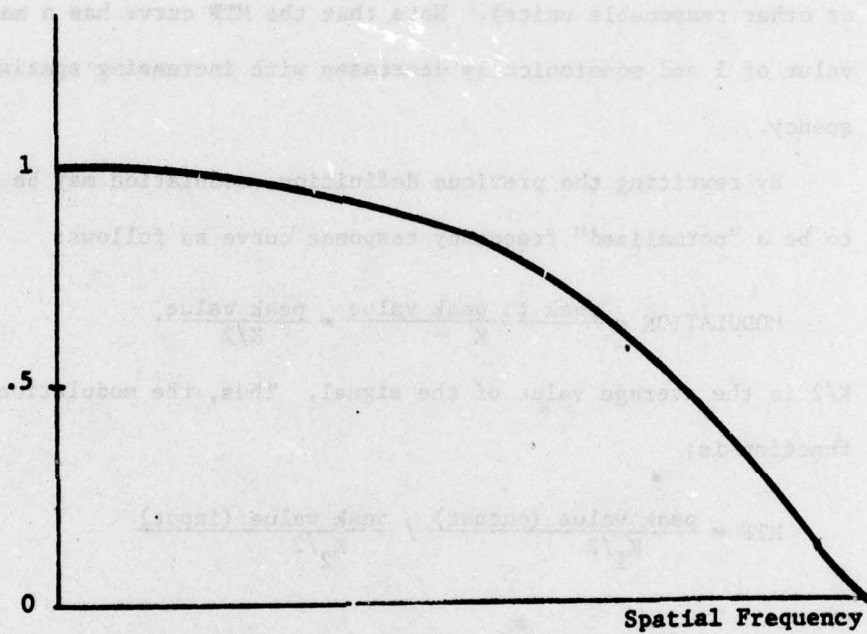
Figure 3.

Photometric Measurements for Finding the MTF.

Figure 4.

Typical MTF Curve.

generated by plotting the dimensionless ratio described above as a
function of spatial frequency (cycles per inch, or cycles per degree,
or other reasonable units). Note that the MTF curve has a maximum
value of 1 and monotonically decreases with increasing spatial fre-
quency.

By rewriting the previous definition, modulation may be shown
to be a "normalized" frequency response curve as follows:

$$\text{MODULATION} = \frac{\text{peak to peak value}}{K} = \frac{\text{peak value}}{K/2}.$$

$K/2$ is the average value of the signal. Thus, the modulation transfer
function is:

$$\text{MTF} = \frac{\text{peak value (output)}}{K_1/2} \Big/ \frac{\text{peak value (input)}}{K_2/2}$$

or

$$\text{MTF} = \frac{\text{peak value (output)}}{\text{peak value (input)}} \cdot K_3 .$$

K_3 is the normalizing constant and equals

$$\frac{K_2}{K_1} = \frac{(S_{max} + S_{min})}{(S'_{max} + S'_{min})} = \frac{\text{(average value of input signal)}}{\text{(average value of output signal)}}.$$

Note that the MTF of a CRT is limited by the CRT drive electronics (video
amplifier) bandwidth and the finite size of the CRT spot which is usually
thought to have a gaussian shaped point spread function.

Applying MTF to Matrix Displays

It appears as if MTF may be measured on matrix displays in much the
same way as for a CRT. That is, a sinewave input signal is formed and the

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output measured photometrically. Since the matrix display is made up of discrete elements, however, the measurements would only be made until the spatial frequency was equal to 1/2 the maximum number of elements/display dimension (horizontal or vertical). The above frequency limit indicates that measurements should be made in both horizontal and vertical dimensions. This depends on the method of driving the display, but, in general, it is true.

In a matrix display, the input is sampled to give the discrete output. This sampling process creates frequences which were not present in the input signal. These frequencies are predictable for any given sinusoidal frequency input and may be removed by low pass filtering the measured display output. If the matrix display is used to display a sinewave equal in frequency to one half the number of display elements (actually slightly lower), then an ideal low pass filter would be used.

Apparently, as used for matrix displays, MTF refers to the maximum recoverable sinewave modulation after suitable filtering. That is, knowing the input signal modulation, one may multiply by the matrix display system MTF to find the maximum recoverable sinewave modulation that would be available in the measured output after filtering.

In this sense, MTF is useful. In fact, for displays of sufficiently high density, the human visual system performs this filtering operation and removes the sidebands generated by the sampling process. This gives the display a continuous non-matrix appearance.

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In any sampled system, one must give consideration to the input signal spectrum. If the input signal is not sufficiently band-limited, aliasing problems occur and must be considered.

Estimating the MTF of the Hughes Liquid Crystal Matrix Display

An analytical estimate of the shape of the MTF curve for the Hughes' display can be found using a linear systems approach. Figure 5 shows the system. A hypothetical 1000 X 1000 element one inch square display is assumed. To analyze the response of the matrix display, imagine a perfect matrix where the output of any one cell is equal to the sampled portion of the picture input times a constant and is uniform across the cell, as in Figure 6. If we were to scan across this matrix photometrically, the output might be as shown in Figure 7(a). In Figure 7(b), it is shown how a signal of this form might be generated. Thus, Figure 7 shows that a signal generated by a sample and hold process is identical to the measured matrix display output. The response to a sinewave of such a system is well known and is of a $\frac{\sin x}{x}$ form. Reference [1] explains this fully. Realizing that the display itself gives a sinx/x or sample and hold system response, an estimate of the MTF of the system display, including the initial sample and hold electronics and the drain line electrical response, can be made. Two display outputs will be analyzed, one a vertical sinewave pattern, the other a horizontal sinewave pattern, both of varying spatial frequency. These patterns are illustrated in Figure 8.
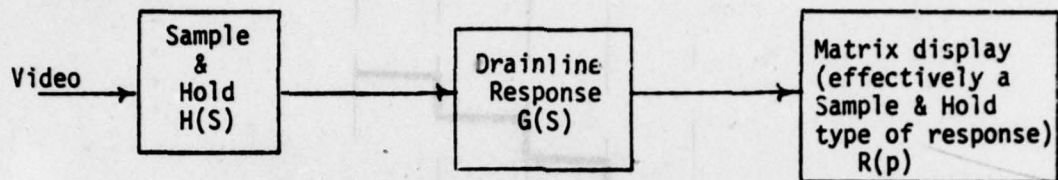
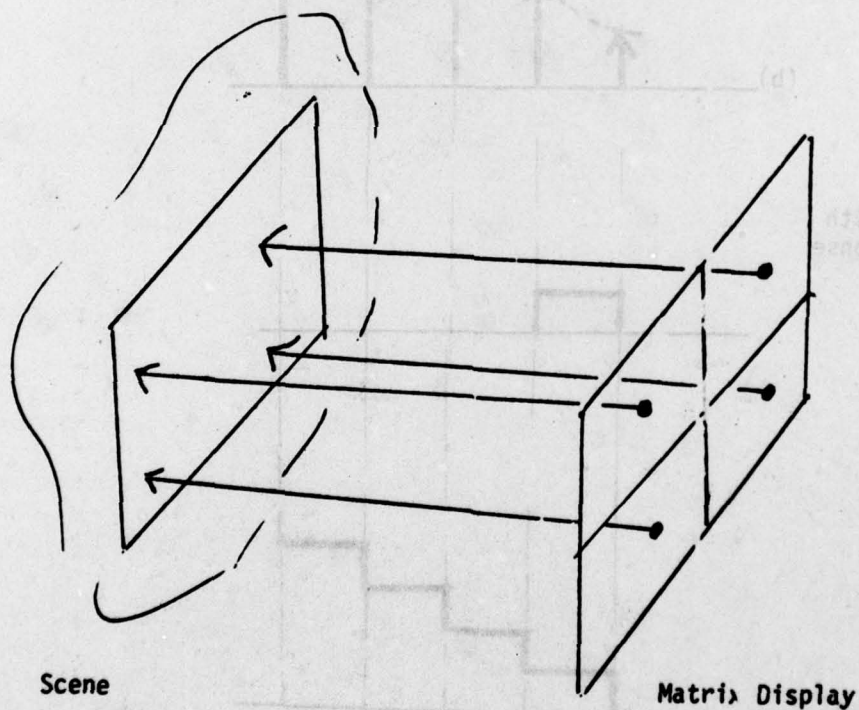Figure 5. System Block Diagram of the Hypothetical
Hughes Liquid-Crystal Display

Scene

Matrix Display

Figure 6. Illustration of Ideal Sampling

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This signal   (a)

is equal to

a sampled
signal   (b)

convolved with
a hold response
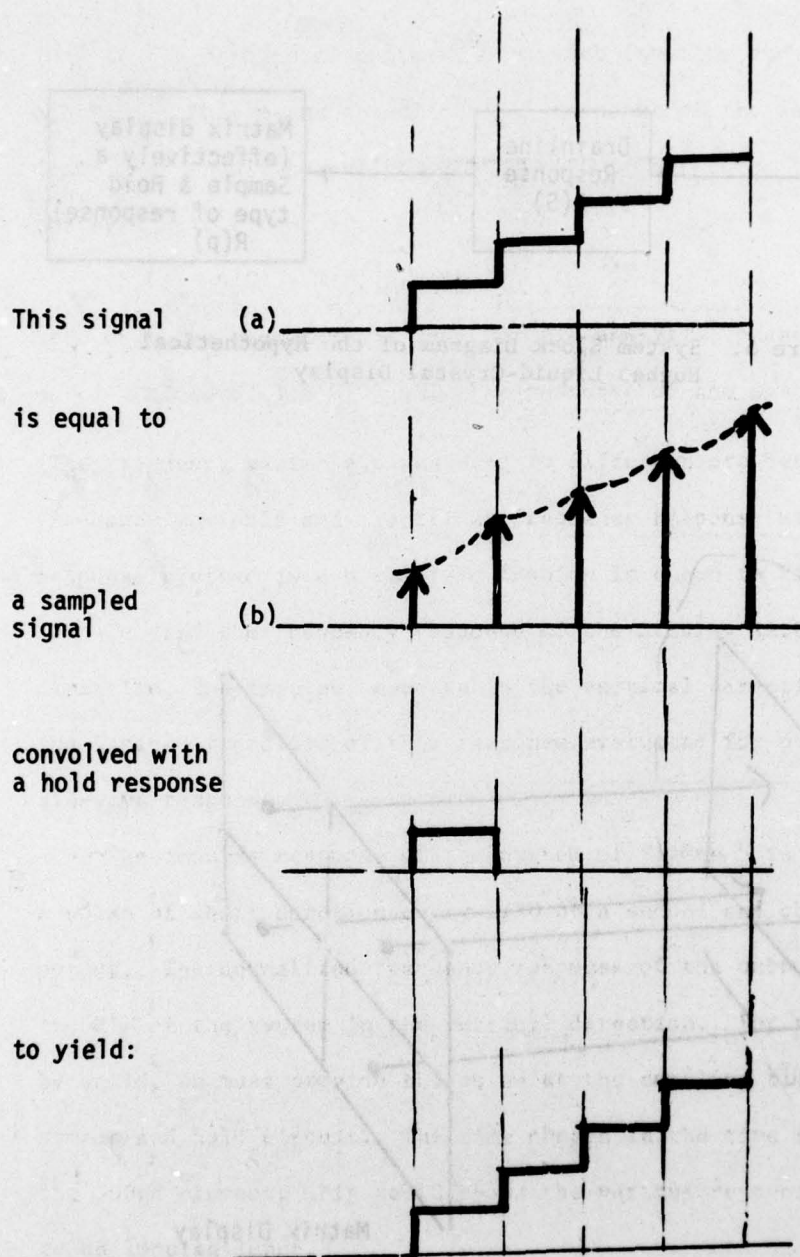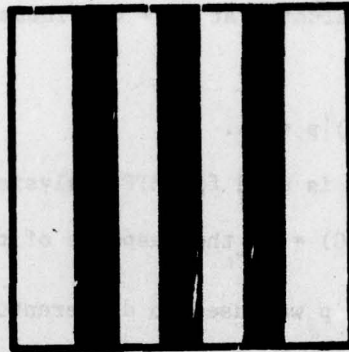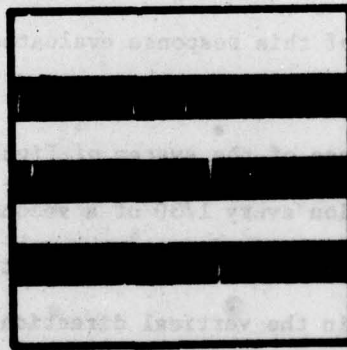
to yield:

Figure 7. Photometric Response Signal and its
           Equivalent Generated by a Sample
           and Hold

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Horizontal Pattern

Vertical Pattern

Figure 8.   Sinewave Patterns used to Analyze the
Hughes' Display (only one frequency
shown)

In the horizontal pattern, the video input to each drain line[1] is a constant[2]. This means the electrical response of the sample and hold and drain line should be evaluated at $j\omega = 0$. Therefore, the response of the system is given by

$$|H(0) \cdot G(0) \cdot R(p)|p = j\lambda.$$

Note only the magnitude is used for MTF analysis; phase is usually ignored. Since $H(0) = G(0) = 1$, the response of the system is $|R(p)|_p = j\lambda$.

(The frequency variable p was used to differentiate between the spatial frequency variable and electrical frequency response variable.) This response plotted in a normalized fashion is shown in Figure 9.
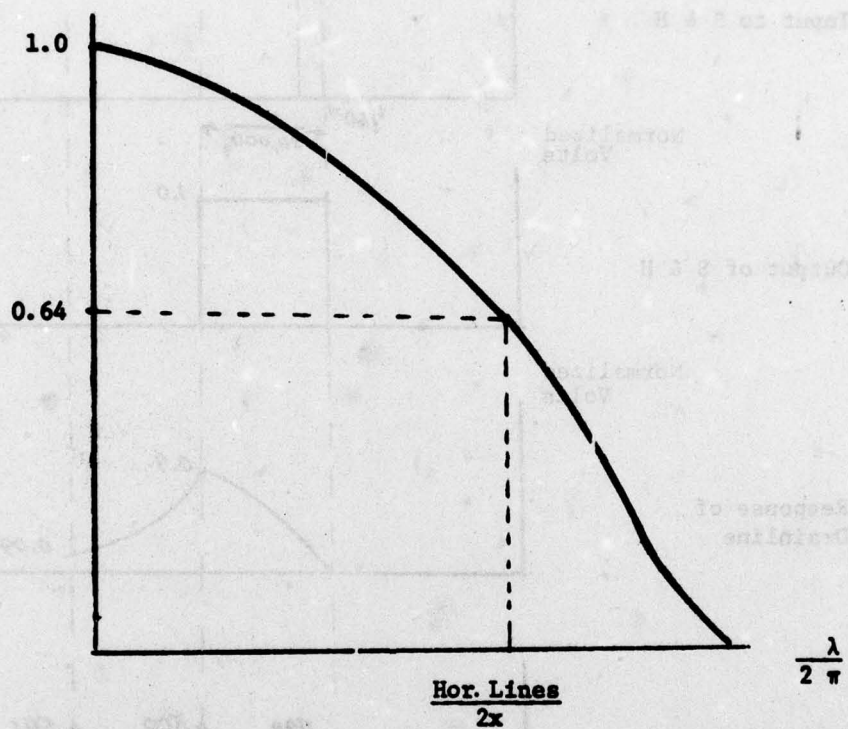
To find the frequency response of the display in the vertical direction, the impulse response in the vertical direction is found and the Laplace transform of this response evaluated for $p = j\lambda$ gives the sinewave response.

The impulse response of the system of Figure 5 is found by applying a pulse of short duration every 1/30 of a second and observing the visual output. The normalized frequency response of the output is approximately the MTF of the system in the vertical direction. For this procedure to be valid, we must provide the pulse at the sampling time of the input sample and hold circuit. The time chosen is the time required to excite the 500th element. Figure 10 shows the various responses of the system to an impulse input.

---

[1] The drain lines in the Hughes' liquid crystal displays used by the Air Force are essentially distributed RC transmission lines. These lines provide a path for the video signal to each of the sample and hold circuits at each elemental cell. It is this stored voltage that controls the luminance of each cell.

[2] In the general matrix display case, this may not be true. Analysis would be accomplished by using a method similar to the method used here to find the frequency response in the vertical direction.

x = inches, degrees, etc.

typical spacial frequency units.
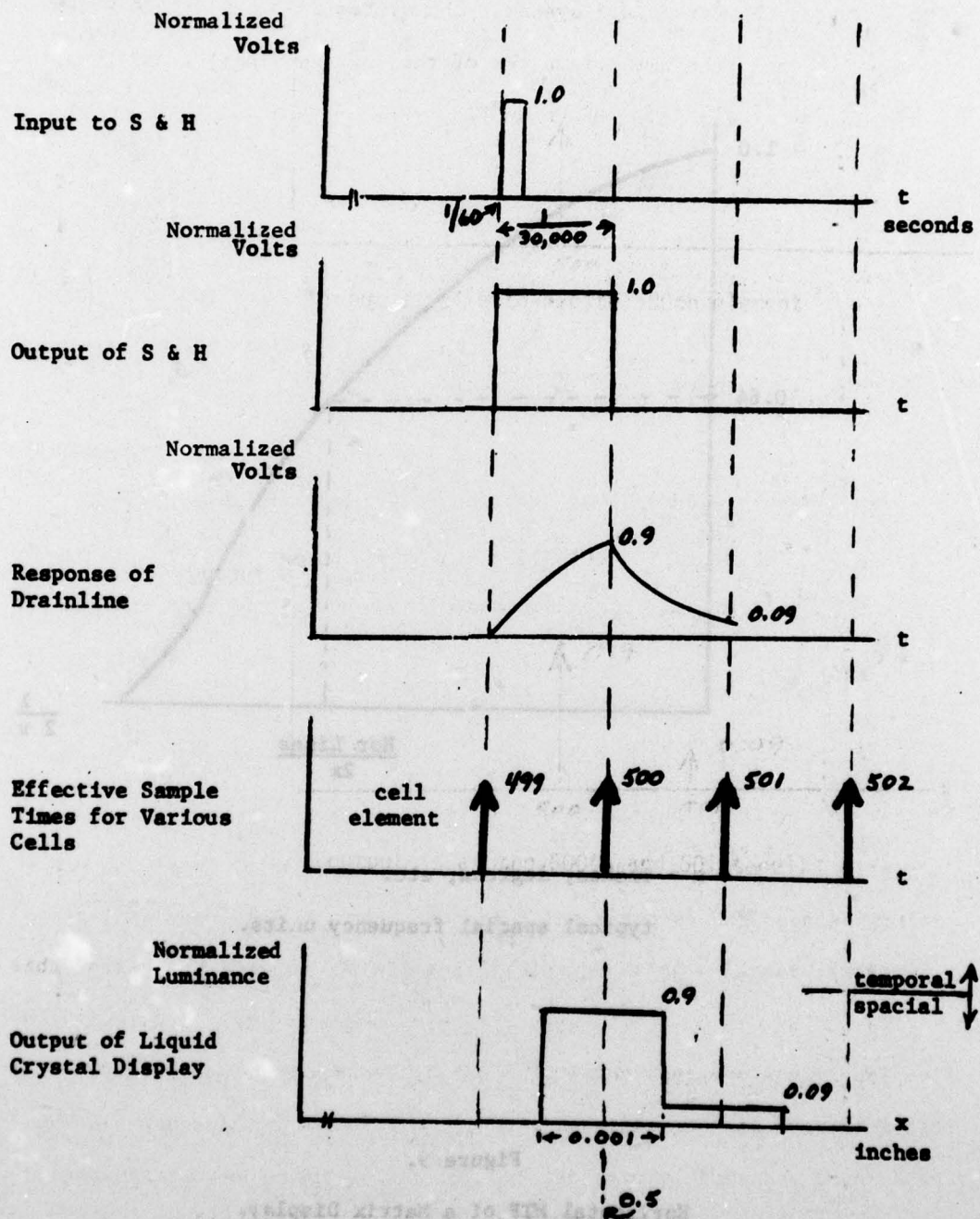
Figure 9.

Horizontal MTF of a Matrix Display.

Figure 10.

Response of System to an Impulse Input.

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Inspection of this response reveals it may more easily be analyzed as a discrete time/space system. The system is still that of Figure 5; however, only the sampled values of the input and output are observed. A single sampled input shown in Figure 10 is equivalent to a Kronecker delta function. The sampled system response to this delta function is shown in Figure 11 along with the input to the system. From these two waveforms, the system difference equation may be found. The frequency response of the system can then be found by z transform techniques. The sampled output is then applied to the liquid crystal display cell (by means of a holding capacitor) and the output is now in analog form spatially. The spatial response of the cell is the familiar $\frac{\sin x}{x}$ response previously discussed.

The difference equation which describes the discrete-time/space response is:

$$y(k) = 0.9\, x(k) + 0.09\, x(k-1).$$

Taking the z transform of both sides yields:

$$y(z) = 0.9\, x(z) + 0.09\, z^{-1}\, x(z).$$

The system transfer function is then $y(z)/x(z)$. Therefore,

$$\frac{y(z)}{x(z)} = H(z) = 0.9 + 0.09z^{-1} = \frac{0.9z + 0.09}{z} = \frac{0.9\,(z + 0.1)}{z}.$$

The pole-zero plot in the z domain is given in Figure 12. From this pole-zero plot, the frequency response magnitude can be obtained by ratioing the vector length of the zero to the "operating point" on the

Input

1

500

input at time to excite 500th element

Output

0.9

0.09

500   501

k
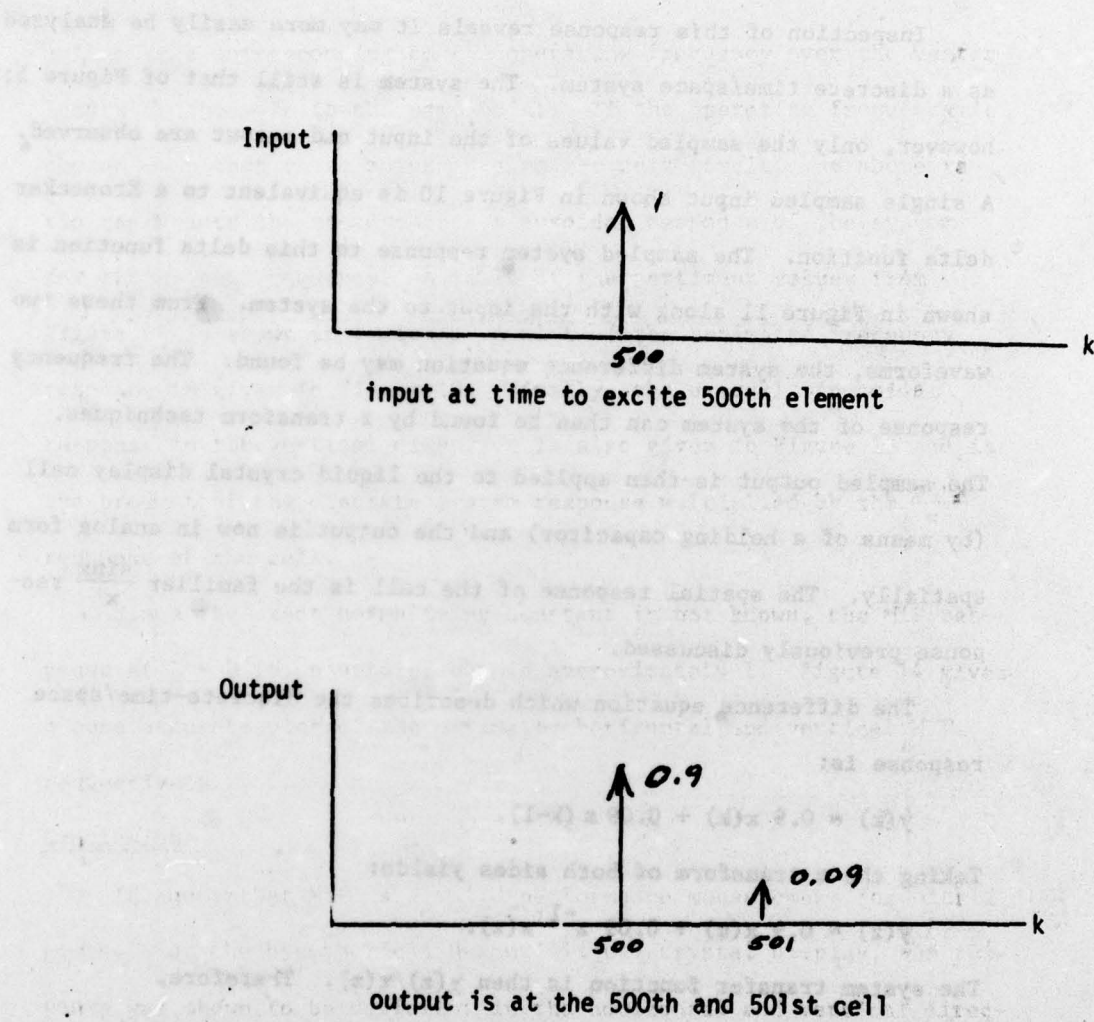
output is at the 500th and 501st cell

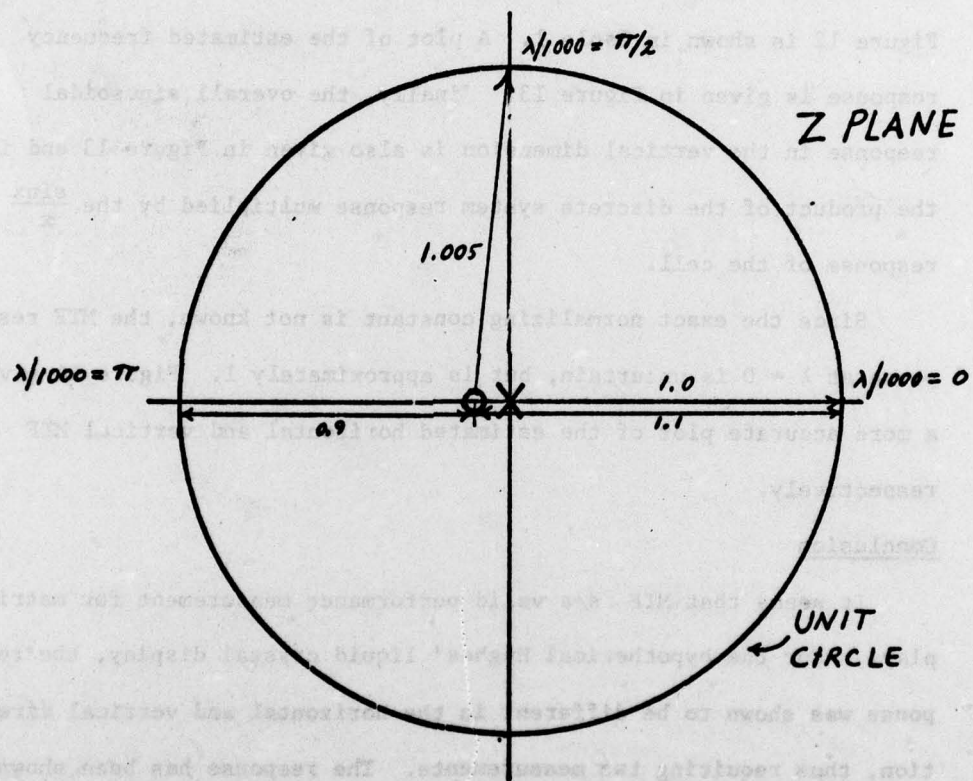Figure 11. Single Sampled Value Input and
the Resulting Output

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Figure 12. Pole-zero plot in Z plane of

$$\frac{0.9\,(Z + 0.1)}{Z}$$

unit circle corresponding to the operating frequency over the vector length of the pole to the same point. If the operating frequency is chosen such that these points are on the unit circle, the above ratio represents the steady-state sinusoidal response of the system for the chosen frequency. A table of the pertinent values from Figure 12 is shown in Table 1. A plot of the estimated frequency response is given in Figure 13. Finally, the overall sinusoidal response in the vertical dimension is also given in Figure 13 and is the product of the discrete system response multiplied by the $\frac{\sin x}{x}$ response of the cell.

Since the exact normalizing constant is not known, the MTF response at $\lambda = 0$ is uncertain, but is approximately 1. Figure 14 gives a more accurate plot of the estimated horizontal and vertical MTF respectively.

Conclusion

It seems that MTF is a valid performance measurement for matrix displays. For the hypothetical Hughes' liquid crystal display, the response was shown to be different in the horizontal and vertical direction, thus requiring two measurements. The response has been shown for a hypothetical 1000 X 1000 element display by using a linear systems approach.

This procedure was based on the assumption that the individual cell response was uniform across the display, and that the cell response did not overlap any adjacent cells. In the laboratory, this has been shown

Table 1

Pertinent Values Taken from Pole-Zero Plot of

$$\frac{0.9\,(Z + 0.1)}{Z}$$

op = 1 $\underline{/\lambda X}$ = 1 $\underline{/0.001\lambda}$ =	$V_z \to op$	$V_p \to op$	Ratio	Ratio X 0.9*
1 $\underline{/0}$	1.1	1.0	1.1	0.99
1 $\underline{/\pi/2}$	1.005	1.0	1.005	0.90
1 $\underline{/\pi}$	0.9	1.0	0.9	0.81

* from transfer function.

NOTE: The notation $V_p \to op$ and $V_z \to op$ represents the magnitude of the vector length from the pole to the operating point and the zero to the operating point respectively.
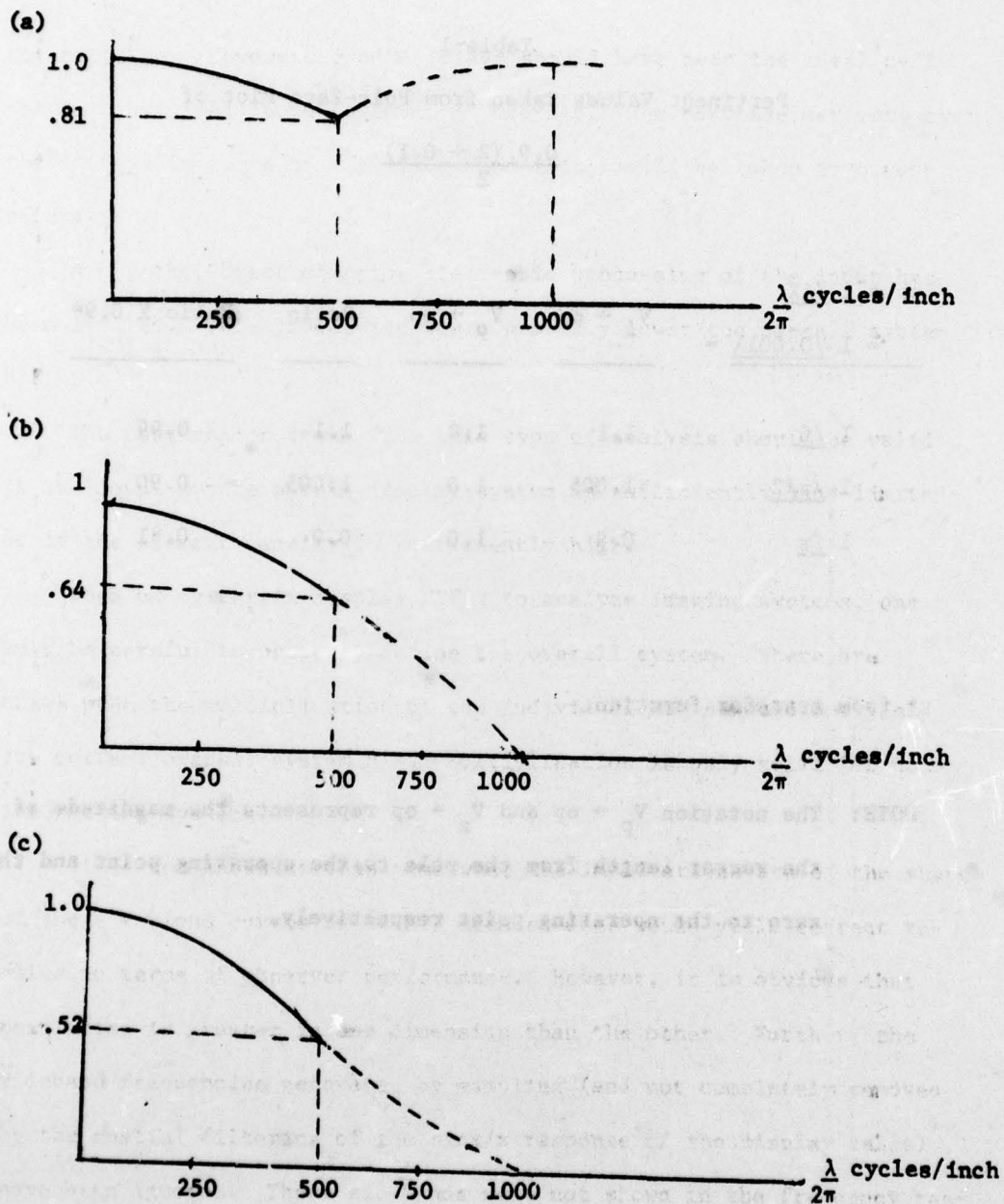
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(a)

(b)

(c)

Figure 13. System Response

(a) Response of Discrete System.
(b) Response of Matrix (sinx/x).
(c) Product of (a) & (b).

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λ/2π cycles/inch.

This area not pertinent due to frequency limit of input of 500 cycles/inch.
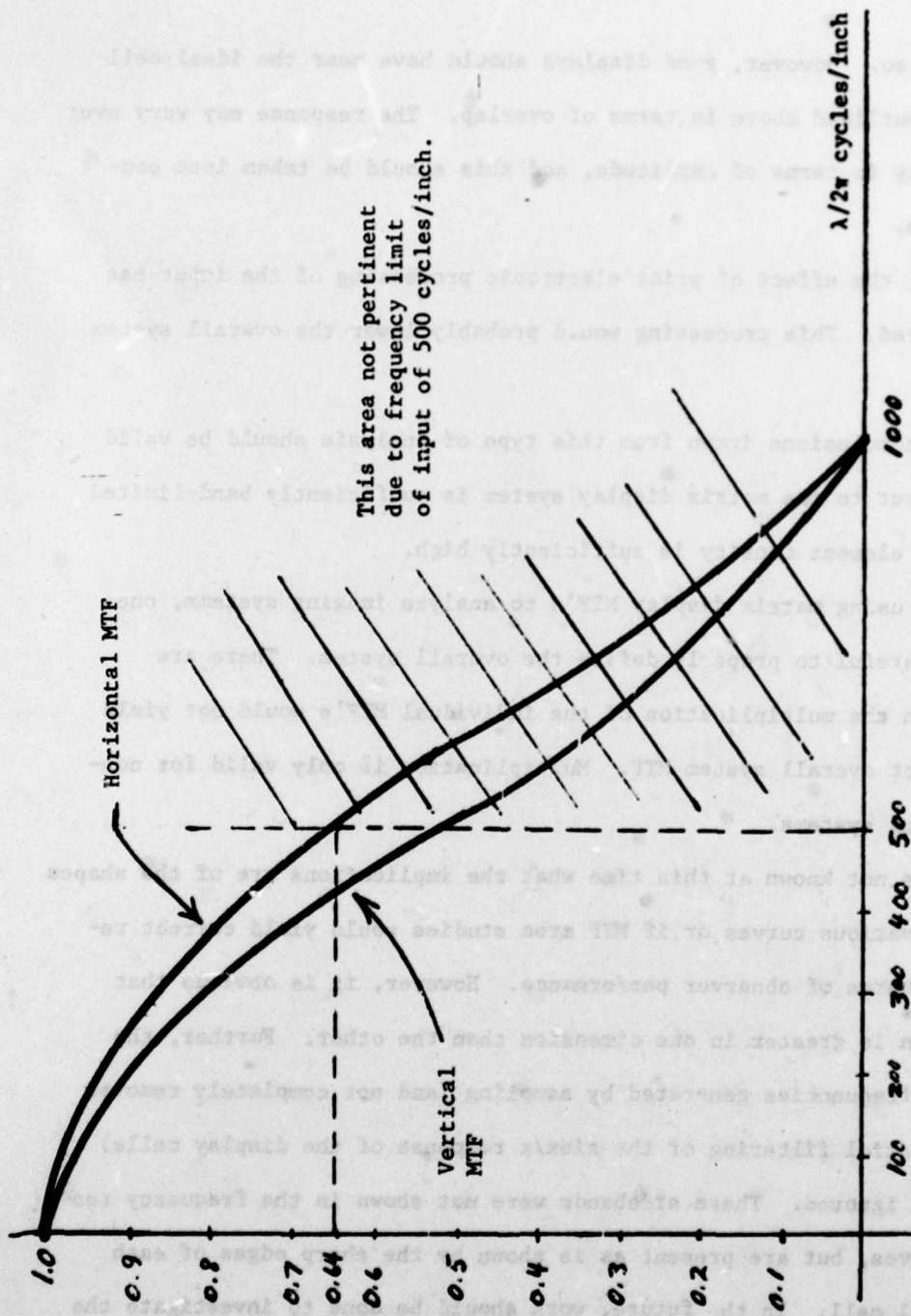
Horizontal MTF

Vertical MTF

Figure 14.

Estimated MTF of Hypothetical 1000 X 1000 Element Hughes' Liquid Crystal Display in Horizontal and Vertical Directions

not to be so. However, good displays should have near the ideal cell response outlined above in terms of overlap. The response may vary over the display in terms of amplitude, and this should be taken into consideration.

Also, the effect of prior electronic processing of the input has been ignored. This processing would probably lower the overall system MTF.

The conclusions drawn from this type of analysis should be valid if the input to the matrix display system is sufficiently band-limited or if the element density is sufficiently high.

When using matrix display MTF's to analyze imaging systems, one must be careful to properly define the overall system. There are cases when the multiplication of the individual MTF's would not yield the correct overall system MTF. Multiplication is only valid for non-interacting systems.

It is not known at this time what the implications are of the shapes of these various curves or if MTF area studies would yield correct results in terms of observer performance. However, it is obvious that resolution is greater in one dimension than the other. Further, the sideband frequencies generated by sampling (and not completely removed by the spatial filtering of the sinx/x response of the display cells) have been ignored. These sidebands were not shown in the frequency response curves, but are present as is shown by the sharp edges of each individual cell. In the future, work should be done to investigate the

implications of the shape of the MTF curves in terms of MTF area analysis. The effects of sideband generation should also be considered, especially if the matrix display is not sufficiently dense to place these frequencies outside or in a low response region of the human visual system MTF.

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